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13. ABSTRACT *(Maximum 200 words)*

A non-local closure numerical model based on the Transilient Turbulence Theory (TTT) (Stull, 1984-1986) has been developed and verified in and above a homogeneous tree canopy. The first order, volumetrically averaged governing equations for momentum, heat, and humidity were coupled dynamically with canopy processes such as evapotranspiration and radiation within the canopy. The simulated profiles of momentum, heat, and humidity were compared to measurements in a homogeneous orchard during project WIND. The model provides evidence that non-local turbulence closure by TTT is a consistent and efficient technique to parameterize the turbulent transport near the ground in canopies as well as above, and can be incorporated into numerical models.

The spatial resolution in surface parameterizations for spatially distributed models was quantified using spatial autocorrelations. The resulting error prediction model was used to quantify the statistical errors due averaging different patch sizes and contrasts. Sensitivity of process models to these averaging errors in boundary conditions was quantified using probable error vectors.

Overall these efforts have rigorously set the stage for future use of the non-local turbulent transport approach and as an efficient and accurate method to model spatially distributed canopy flow in three dimensions

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A Study of Planetary Boundary Layer Forcing on Turbulent Flow Characteristics in Tree Canopies Using Project Wind Data

Final Progress Report

David R. Miller and X. Harrison Yang

February 28, 1997

U. S. Army Research Office
Grant Number DAAH04-94-G-0049

Department of Natural Resources Management and Engineering
University of Connecticut

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A. STATEMENT OF THE PROBLEM STUDIED.

The primary purpose of this project was to develop a Transilient Turbulence non-local closure model of the wind and energy flux in tree canopies which would realistically couple the roughness layer wind field with the wind field above the canopy.

B. SUMMARY OF MOST IMPORTANT RESULTS

A non-local closure numerical model based on the Transilient Turbulence Theory (TTT) (Stull, 1984-1986) has been developed and verified in and above a homogeneous tree canopy. The first-order, volumetrically averaged governing equations for momentum, heat, and humidity were coupled dynamically with canopy processes such as evapotranspiration and radiation within the canopy. The simulated profiles of momentum, heat, and humidity were compared to measurements in a homogeneous orchard during project WIND. The model provides evidence that nonlocal turbulence closure by TTT is a consistent and efficient technique to parameterize the turbulent transport near the ground in canopies as well as above, and can be incorporated into numerical models. The Appendix of this report contains the documentation of the model.

The project WIND data sets from the almond orchard were summarized into wind direction and stability classes and utilized to verify the model.

The TTT approach to modeling canopy fluxes and coupling them to the PBL turned out to be very sensitive to accurate specification of the surface boundary conditions. Therefore an investigation into the accuracy of spatially averaging the surface boundary conditions was conducted. The spatial resolution in surface parameterizations for spatially distributed models was quantified using spatial autocorrelations. The resulting error prediction model was used to quantify the statistical errors due averaging different patch sizes and contrasts. Sensitivity of process models to these averaging errors in boundary conditions was quantified using probable error vectors.

Overall these efforts have rigorously set the stage for future use of the non- local turbulent transport approach and as an efficient and accurate method to model spatially distributed canopy flow in three dimensions.

C. LIST OF PUBLICATIONS AND TECHNICAL REPORTS

Bresnahan, P. A., D.L. Civco, and D. R. Miller. 1997. Spatial Resolution Error in A Regional Process Model:Interaction Between Model Sensitivity and Parameter Error. Remote Sensing of the Environ (Submitted).

Bresnahan, P. A. and D. R. Miller. 1997. Quantifying and Predicting the Effects of Surface Patch Size and Patch Contrast on Spatial Resolution Error in Simulated Landscapes. J. Climate (Submitted).

Bresnahan, P. A. and D. R. Miller. 1997. Choice of Data Scale: Predicting Resolution Error in a Regional Evapotranspiration Model. Agr & Forest Meteorol. (In Press).

Miller, D. R. and R. M. Cionco. 1995. Measurement of zero-plane displacement in tree stands using within-canopy wind and leaf area density profiles. Proc. 22nd Conf on Agr and For. Meteorology of the AMS.

Bresnahan, P. A. and D. R. Miller. 1995. Effects of Surface Cover Heterogeneity on Spatial Averaging Error in a Regional Evapotranspiration Model. Proc. 22nd Conf on Agr and For Meteorology of the AMS.

Cionco, R. M. and D. R. Miller. 1995. Behavior of Wind Fields Through Tree Stand Edges. Proce. 22nd Conf on Agr and For Meteorology of the AMS.

Yang, X., W. Ni and D. R. Miller. 1994. Application of Transilient Turbulence Theory to Model Turbulent Transport Processes in Vegetation. Proc 21st Conf on Agr and For Meteorology of the AMS. pp 84-85.

Bresnahan, Patricia A. 1996. Sensitivity of A Regional Evaptranspiration Model to The Spatial Averaging of Parameters. PhD Dissertation, University of Connecticut. Storrs, CT. 146p.

Thistle, H. W. and D. R. Miller. 1997. The Wind Flow Field Through a Forest Edge: A Comparison of Foliated and Unfoliated Canopies. Agr. & Forest Meteorol. (Submitted).

He, Yuguang. 1995. Modeling the Plant Canopy Micrometeorology with Transilient Turbulence Theory. Storrs Agriculture Experiment Station Technical Report. College of Agriculture and Natural Resources, University of Connecticut, Storrs, CT 06269-4087. 160p.

Wang, Yanshuo. 1996. Coupling of Small Scale Turbulence Near the Ground to large Eddy Structures in a Desert Boundary Layer. MS Thesis. University of Connecticut. Storrs CT. 06269-4087.

Manuscripts in preparation:

He, Yuguang. A Transilient Turbulence Model of Plant Canopy Micrometeorology. PhD dissertation. (In prep)

Miller, D.R. and Y. Wang. Wavelet methods to detect the coupling of large eddy structures to surface layer processes.

D. PARTICIPATING SCIENTIFIC PERSONNEL

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E. APPENDIX

Canopy Model Configuration

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February 26, 1997

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A. Physical Configuration of the Model

The model is one dimensional and horizontally homogeneous with different vertical spacings and timesteps in three regions. The first is called the roughness sublayer region which extends from the ground surface up to four tree heights. In this region, the vertical spacing is $\Delta z = 1\ \mathrm{m}$ and the timestep is $\Delta t = 3.6\ \mathrm{sec}$.

The second region extend from four to ten tree heights. The vertical spacing is $\Delta z = 10\ \mathrm{m}$, and the timestep is $\Delta t = 36\ \mathrm{sec}$. The combination of the first and second regions may be seen as the surface layer.

From the ten tree heights up to the top of the planetary boundary layer (PBL: ~3 km), the vertical spacing is $\Delta z = 100\ \mathrm{m}$, and the timestep is $\Delta t = 360\ \mathrm{sec}$.

The simulation area is divided into three regions because the distinguishing characteristics of these layers are different in response to the thermodynamic forcings within the PBL. Within the roughness sublayer, the turbulence is often characterized by high intensity and large skewness and kurtosis, which indicates that the turbulence is non-Gaussian and intermittent. This is true in all sizes of canopies from tall forests (Baldocchi and Hutchison, 1987; Baldocchi and Meyers, 1988) to short grass (Aylor *et al.*, 1993).

Above the roughness sublayer, however, the turbulence can be properly described by the Gaussian distribution as over a flat plain (Kaimal and Finnigan, 1994; Seginer *et al.*, 1976).

The use of an intermediate region is due to both physical and numerical concerns. The surface layer, which extends from the ground surface to about 100 m, is observed to be decoupled from the mixing layer at night and only strong instability can break the surface inversion layer produced at night, requiring special consideration in the model. Also in order to keep the numerical scheme smooth in terms of vertical spacing and timestep, it is necessary to have this intermediate region to avoid jumping between two extreme timesteps (3.6 sec and 360 sec).

Reference

Aylor, D. E., Wang, Y. Y., Miller, D. R.: 1993, 'Intermittent wind close to the ground within a grass canopy', *Bound.-Layer Meteorol.* **66**, 427-448.

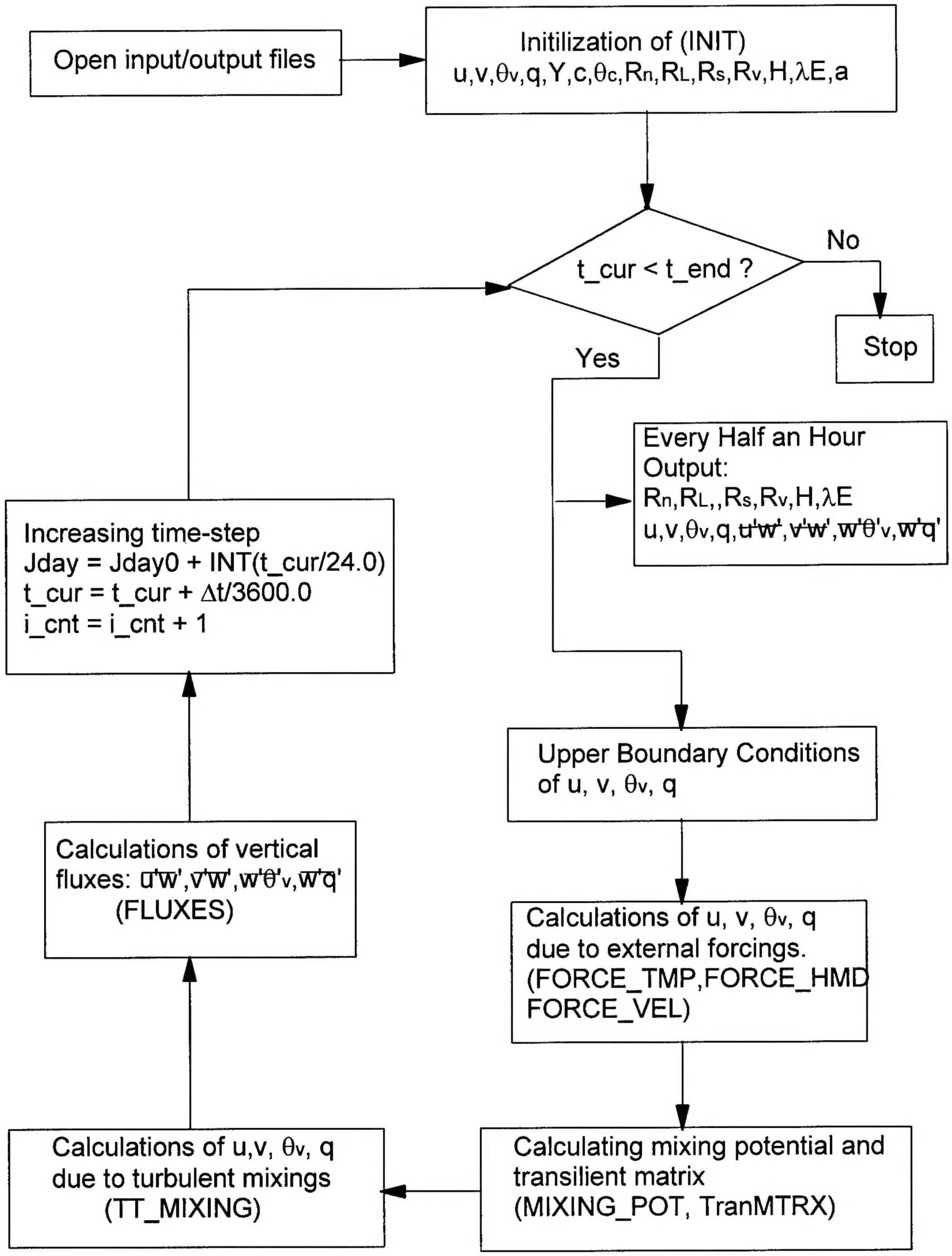
Baldocchi, D. D., and Hutchison, B. A.: 1987, 'Turbulence in an almond orchard: Vertical variation in turbulent statistics', *Bound.-Layer Meteorol.* **40**, 127-146.

Baldocchi, D. D., and Meyers, T. P.: 1988, 'Turbulence structure in a deciduous forest', *Bound.-Layer Meteorol.* **43**, 345-364.

Kaimal, J. C. and Finnigan, J. L.: 1994, *Atmospheric Boundary Layer Flows - Their Structure and Measurement*, Oxford University Press, New York, 289 pp.

Seginer, I., Mulhearn, P. J., Bradley, E. F., and Finnigan, J. J.: 1976, 'Turbulent flow in a model plant canopy', *Bound.-Layer Meteorol.* **10**, 423-453.

*Flowchart of the Model**



* This is the flowchart for the main (control) program of the model, which is named as **CAN_MAIN**. The programs and symbols are explained in the following text.

Leaf Area Index and Leaf Area Density (LF)

Algorithm

The cumulative leaf area index (L: m^2 m^{-2}) of a canopy is calculated using Weibull's cumulative distribution function following Yang *et al.* (1995),

$$L(z) = \mathrm{LAI0} \times \left\{1 - \exp\left[-\left(\frac{1 - z/H}{b}\right)^c\right]\right\} \tag{LF.1}$$

where LAI represents the leaf area index excluding stems, z is the height in meters above the ground, H is the tree height in meters, and b and c are the two parameters specific to the canopy structures. The program for Eq.(LF.1) is named as **CUM_LAI(z)**.

Eq.(LF.1) may be properly used for the distribution of radiation. In consideration of the drag of the canopy, stems and trunks should be also included, although they do not participate in the radiation budget. By adding one linear term for the trunk, Eq.(LF.1) may be modified as

$$L(z) = \mathrm{LAI1} \times \left\{1 - \exp\left[-\left(\frac{1 - z/H}{b}\right)^c\right]\right\} + 0..3 \cdot \left(1 - z/H\right) \tag{LF.2}$$

where LAI1 is leaf area index including stems. The program is named as **CUM_LAI0(z)**.

The leaf area density (a: m^2 m^{-3}) is evaluated according to its definition

$$a(z) = \frac{dL(z)}{dz} \tag{LF.3}$$

which yields, from the discretization of equation (LF.2),

$$a(z) = \frac{L(z + \Delta z/2) - L(z - \Delta z/2)}{\Delta z} \tag{LF.4}$$

where Δz is the vertical spacing. The corresponding programs of leaf area density to Eqs.(LF.1) and (LF.2) are named

LEAF_AREA_DENSITY(z)

and

LEAF_AREA_DENSITY0(z),

respectively.

Reference

Yang, X., Miller, D. R., and Witcosky, J. J.: 1994, 'Characterization of hardwood forest canopies in the eastern United States', *21st Conference on Agriculture and Forest Meteorology*, March 7-11, 1994, 130-133.

Boundary Layer Resistance (BR)

Algorithm

Following Goudriaan (1977), the boundary layer resistance (r_b: s m^{-1}) of the foliage at each grid box may be estimated as

$$r_b = 0.5 \times 1.8 \times 10^2 \times \frac{dl}{M^2} \tag{BR.1}$$

where *dl* is the characteristic width of leaves, and $M = \sqrt{u^2 + v^2}$ is the mean wind speed.

Program

The function boundary layer resistance is named as

BL_RESISTANCE(u,v)

where **u** and **v** represent the two components of the wind velocity.

Reference

Goudriaan, 1977: *Crop Micrometeorology: A Simulation Study*, 249 pp.

Stomatal Resistance (SR)

Algorithm

As has been discussed by Norman (1979), the stomatal resistance (r_S) strongly depends on the irradiance on the leaves and the bio-physical conditions of the leaves. It may be expressed as

$$r_s = f_1(R_v) f_2(\theta_c) / f_3(\psi_{lw}) \qquad \text{(SR.1)}$$

where f_1, f_2, and f_3 are functional representations, R_V is the visible (or photosynthetically active) radiation the leaves received, ψ_{lw} is the leaf water potential. Norman (1979) suggests that the three functions be given as

$$f_1(R_v) = \frac{r_{s,\min}\left[R_v^*\left(\frac{r_s^*}{r_{s,\min}} - 1\right) + R_v\right]}{\frac{r_{s,\min}}{r_{\text{cuticle}}}\left[R_v^*\left(\frac{r_s^*}{r_{s,\min}} - 1\right) + R_v\right] + R_v}, \qquad \text{(SR.2)}$$

$$f_2(\theta_c) = \begin{cases} 1 + m \cdot \left[\dfrac{\theta_c - \theta_{c,\min}}{\theta_{c,U} - \theta_{c,\min}}\right]^6 & \text{for } \theta_c > \theta_{c,\min} \\ 1 + m \cdot \left[\dfrac{\theta_{c,\min} - \theta_c}{\theta_{c,\min} - \theta_{c,L}}\right]^6 & \text{for } \theta_c < \theta_{c,\min} \end{cases}, \qquad \text{(SR.3)}$$

$$f_3(\psi_{lw}) = \begin{cases} 1 & \psi_{lw} > \psi_{lw}^{(1)} \\ \dfrac{\psi_{lw} - \psi_{lw}^{(2)}}{\psi_{lw}^{(1)} - \psi_{lw}^{(2)}} & \psi_{lw}^{(1)} > \psi_{lw} > \psi_{lw}^{(2)} \\ 0 & \psi_{lw} < \psi_{lw}^{(2)} \end{cases} \qquad \text{(SR.4)}$$

where the parameters in the three functions are listed in TABLE I.

TABLE I

Parameter Values and Interpretations in the Three Functions for the Calculation of the Stomatal Resistance.

Symbols	Values	Interpretation

$f_1(R_V)$ (equation (SR.2))

$r_{S,\min}$	200 s m^{-1}	minimum stomatal resistance
R_v^*	100 W m^{-2}	critical visible radiation
r_s^*	400 s m^{-1}	critical stomatal resistance
r_{cuticle}	3000 s m^{-1}	cuticular resistance
$f_2(\theta_C)$ (equation (SR.3))		
m	5	fitting parameter
$\theta_{C,\min}$	30 °C	temperature corresponding to the minimal $f_2(\theta_C)$
$\theta_{c,L}$	15 °C	lower reference temperature
$\theta_{c,U}$	45 °C	upper reference temperature
$f_3(\psi_{lw})$ (equation (SR.4))		
$\psi_{lw}^{(1)}$	-12 bars	upper reference water potential
$\psi_{lw}^{(2)}$	-17 bars	lower reference water potential

Program

The subroutine is named as

STOMA_RESISTANCE(rs,RV,Tc)

where **rs** represents the stomatal resistance as the output. The inputs are the visible radiation (**RV**) and the canopy temperature (**Tc**).

Reference

Norman, J. M.: 1979, 'Modeling the complete crop canopy', In: *Modification of the Aerial Environment of Crops, ASAE Monograph*, 249-311.

Irradiance (IR)

Algorithms

Following Goudriaan (1977), the net irradiance within each grid box is represented as

$$R_{\mathrm{net}} = \alpha_{\mathrm{v}} R_{\mathrm{v,net}} + \alpha_{\mathrm{NIR}} R_{\mathrm{NIR,net}} + R_{\mathrm{L,net}} \tag{IR.1}$$

where R_{net}, $R_{\mathrm{v,net}}$, and $R_{\mathrm{NIR,net}}$ represent the (total) net, the visible, and the near infrared irradiances, respectively; and R_{L} represents the net longwave radiation in the grid box; α_{v} and α_{NIR} represent the absorption coefficients of the leaves for the visible and the near infrared wavebands, respectively. The ultraviolet irradiance is not included in the study for its negligible contribution to the total radiation (Goudriaan, 1977).

In equation (IR.1), the visible ($R_{\mathrm{v,net}}$) and near infrared ($R_{\mathrm{NIR,net}}$) irradiances are further categorized into direct (or beam) and diffuse parts, respectively. The profiles of direct and diffuse irradiances within the canopy are calculated following exponential extinction relationship

$$R = R_{\mathrm{top}} \exp(-KL) \tag{IR.2}$$

where R represents the direct (beam) or diffuse irradiance of either the visible or the near infrared, R_{top} represents the incoming radiation at the top of the canopy, K represents the extinction coefficient of the radiation within the canopy, and L is the cumulative leaf area index defined in equation (LF.1).

The study is designed for a clear sky so that the visible and the near infrared radiation contribute evenly to the total shortwave radiation, given that the ultraviolet part is neglected.

The partition of the direct and the diffuse radiation at the top of the canopy follows the relationship

$$f_D = \frac{0.0837}{\sin\alpha} + 0.3 \tag{IR.3}$$

$$f_B = 1 - f_D \tag{IR.4}$$

where f_D and f_B are the partition coefficients for the diffuse and direct radiation, respectively. Equations (IR.3) and (IR.4) were obtained by linear regression according to the numerical values given by Goudriaan (1977). The solar altitude, $\sin\alpha$, is given by Bras (1990) as

$$\sin\alpha = \sin\delta\sin\Phi + \cos\delta\cos\Phi\cos\psi\,, \tag{IR.5}$$

where δ, Φ, and ψ are declination of the sun, local latitude, and the hour angle of the sun, respectively. The declination of the sun is given as

$$\delta = \frac{23.45\pi}{180}\cos\left[\frac{2\pi}{365}(172 - D)\right], \tag{IR.6}$$

where D is the Julian day ($1 \le D \le 365$ or 366) and δ is in radians.

The local hour angle, $0 \le \psi \le 2\pi$, is given as

$$\psi = \begin{cases} \frac{\pi}{12}\left(T_S + 12 - \Delta T\right) & \text{when the sun is east of the observer's longitude,} \\ \frac{\pi}{12}\left(T_S - 12 - \Delta T\right) & \text{when the sun is west of the observer's longitude,} \end{cases} \tag{IR.7}$$

where T_S is the standard time in the time zone of the observer in hours counted from midnight (0.00-23.59), ΔT is the time difference between standard and local longitude in hours given as

$$\Delta T = \frac{i}{15}\left(\theta_S - \theta_L\right), \tag{IR.8}$$

where i = -1 for west longitude and i = 1 for east longitude, relative to Greenwich, θ_S is the standard meridian (meridian where the observer's time zone is centered), and θ_L is the longitude of the observer meridian.

In equation (IR.2), the extinction coefficient for the direct (beam) radiation is given as

$$K_b = \frac{\overline{O}(\alpha)\cdot(1-\sigma)^{1/2}}{\sin\alpha}, \tag{IR.9}$$

where $\overline{O}(\alpha)$ is the average projection given as

$$\overline{O}(\beta) = O_1 + 0.877(1 - 2O_1)\sin\alpha\,, \tag{IR.10}$$

with

$$O_1 = 0.5 - 0.633\chi_L - 0.33\chi_L^2 \qquad -0.4 < \chi_L < 0.6\,, \tag{IR.11}$$

$$\chi_L = \pm\frac{1}{2}\left(\left|0.134 - \sum_{\lambda=1}^{3} F(\lambda)\right| + \left|0.366 - \sum_{\lambda=4}^{6} F(\lambda)\right| + \left|0.5 - \sum_{\lambda=7}^{9} F(\lambda)\right|\right), \tag{IR.12}$$

where O_1 is an intermediate function, and χ_L represents the deviation of the actual leaf angle distribution from the spherical one. The sign of χ_L is the same as that of the last term.

The function $F(\lambda)$ in equation (IR.12) describes the leaf inclination distribution. For this study, it is assumed that the leaf inclination is isotropic so that $F(\lambda) = 1/9$ in each leaf angle class. However, it may be more accurate for the calculation of χ_L if the measurement of $F(\lambda)$ is known.

In equation (IR.9), σ is defined from the simplification of the leaf reflection (ρ) and transmission (τ) coefficients as $\rho = \tau = 0.5\sigma$.

The extinction coefficient for the diffuse radiation within the canopy is given as

$$K_d = -\frac{1}{L}\ln\left(\sum_{n=1}^{9} B_u(\beta_n)\exp\{-K_b(\beta_n)L\}\right), \tag{IR.13}$$

where $B_u(\beta_n)$ denotes the distribution of the diffuse light over the inclination class β_n under the assumption that the sky has a uniform radiance,

$$B_u(\beta_n) = -\frac{1}{2}\left\{\cos\left[\frac{n\pi}{9}\right] - \cos\left[\frac{(n-1)\pi}{9}\right]\right\} \quad \text{for } n = 1,2,\cdots,9. \tag{IR.14}$$

The inclination of the diffuse light is given as

$$\beta_n = \frac{\pi}{180}\{10(n-1)+5\} \quad \text{for } n = 1,2,\cdots,9. \tag{IR.15}$$

The extinction coefficient K_b in equation (IR.13) is given by equation (IR.9) except that the solar inclination angle α is now replaced by the angle of the diffuse light of the nine inclination classes β_n (n = 1, 2, ..., 9).

For the calculation of longwave radiation, it is assumed that the canopy as a whole exchanges energy first with the clear sky and then redistribute the gain/loss of the energy within the canopy according to exponential extinction relationship. Mathematically, the exchange of longwave radiation between the sky and the canopy is written as

$$B_L = \varepsilon_{\mathrm{sky}} \sigma \theta_{sky}^4 - \varepsilon_{\mathrm{c}} \sigma \theta_{\mathrm{m}}^4, \tag{IR.16}$$

where $\varepsilon_{\mathrm{sky}}$ and ε_{c} are the emissivities of the sky and the canopy, respectively, σ is the Stefan-Boltzmann constant which has the value 5.67×10^{-8} W m^{-2}, θ_{sky} is the apparent potential temperature of the sky, and θ_{m} is the average temperature of the canopy.

According to Idso (1981),

$$\varepsilon_{\mathrm{sky}} = 0.70 + 5.95 \times 10^{-7} e \cdot \exp\left(1500/\theta_{\mathrm{sky}}\right) \tag{IR.17}$$

where θ_{sky} is the potential air temperature in Kelvin at 2 m height above the canopy. (From the test run of the study, equation (IR.17) may be subject to adjustment in accordance with seasons and locations).

The redistribution of the longwave exchange within the canopy may be estimated as

$$R_L = B_L \exp\left(-K_L L\right), \tag{IR.18}$$

where K_L is the extinction coefficient which has the value 0.81 for the longwave radiation within the canopy (Goudriaan, 1977).

Overall, the net irradiance within ith grid box in the canopy is calculated by equation (IR.1). The net irradiance $R_{\mathrm{v,net}}$, $R_{\mathrm{NIR,net}}$, and $R_{\mathrm{L,net}}$ within each grid box are calculated as

$$R_{x,\mathrm{net}} = R_{x,i+1/2} - R_{x,i-1/2} \quad (i = 1,3,5,7), \tag{IR.20}$$

where x represents different wave bands (v: visible; NIR: near infared; L: longwave). The irradiance $R_{x,i+1/2}$ has been prescribed by equation (IR.2) for the visible and near infrared wavebands of direct and diffuse radiation and equation (IR.18) for the longwave radiation. The half grid number indicates that the radiation is computed at even number of heights (0, 2, 4, 6, 8 m) which are presumably the boundaries of the grid boxes.

The total radiation reaching at the top of the canopy may be evaluated by theoretical formula or by the observation as the input. It is summarized by Bras (1990) that the clear sky shortwave radiation, I_C, after accounting for atmospheric effects, as

$$I_c = \frac{W_0}{r^2} (\sin \alpha) \exp\left(-n a_1 m\right), \tag{IR.21}$$

where W_0 is the solar constant (= 1353 W m^{-2}), r is the ratio of actual earth-sun distance to mean earth-sun distance, given by

$$r = 1.0 + 0.017\cos\left[\frac{2\pi}{365}(186 - D)\right], \tag{IR.22}$$

n is a turbidity factor (= 2 for clear mountain air), a_1 is the molecular scattering coefficient defined as

$$a_1 = 0.128 - 0.054\log_{10} m, \tag{IR.23}$$

and m is the effective thickness of the atmosphere (or called optical air mass) estimated as

$$m = \left[\sin\alpha + 0.15(\alpha + 3.885)^{-1.253}\right]^{-1}. \tag{IR.24}$$

Program

The subroutine to calculate the total net irradiance (equation (IR.1)) is

NET_RAD(RN,RV,Ta,Tm,e,j)

where **RN** is the total net irradiance, **RV** is the net visible irradiance which is for the calculation of the stomatal resistance (see equation (SR.2)) and subroutine STOMA_RESISTANCE), **Ta** is the potential air temperature at 2 m above the canopy, **Tm** is the average canopy temperature, and **e** is the vapor pressure, and **j** is the index of the grid box.

The subroutine to calculate the diffuse irradiance (equation (IR.2)) is

DIFFUSE(RD,RD_IN,rhotau,j)

where **RD** is the net output diffuse (visible or near infrared) radiation, **RD_IN** is the input diffuse (visible or near infrared) radiation at the top of the canopy, **rhotau** is the summation of the reflection and transmission coefficients, and **j** is the grid box index.

The subroutine to calculate the net direct irradiance (equation (IR.2)) is

DIRECT(RB,RB_IN,sina,rhotau,j)

where **RB** is the net output direct (visible or near infrared) radiation, **RB_IN** is the input diffuse (visible or near infrared) radiation at the top of the canopy, and **sina** is the solar altitude.

The longwave radiation (equation (IR.18)) is calculated by the subroutine

LONGWAVE(RL,Ta,Tm,e,j)

where **RL** is the net output longwave radiation. The rest variables were explained above.

The extinction coefficient for the diffuse radiation (equation (IR.13)) is given in the subroutine

EXTINCTD(Kd,rhotau)

where **Kd** is the output extinction coefficient for the diffuse radiation.

The extinction coefficient for the direct radiation (equation (IR.9)) is calculated by the subroutine

EXTINCTB(Kf,sina,rhotau)

where **Kf** is the output extinction coefficient for the direct radiation.

The distribution of the diffuse light over the nine inclination class (equation (IR.14)) is given in the subroutine

DIS_TBL(Bu,i)

where **Bu** is the distribution function.

The solar radiation at the top of the canopy (equation (IR.21)) and the partition of the direct and diffuse of both visible and near infrared radiation are given in the subroutine

SOLAR_RAD(RD_V,RD_NIR,RB_V,RB_NIR,sina)

Reference

Bras, R. L.: 1990, *Hydrology*. Andison-Wesley Publishing Company, New York, 643 pp.

Goudriaan, J.: 1977, *Crop Micrometeorology: A Simulation Study*. PUDOC, Center for Agric. Publ. and Doc. Wageningen, The Netherland, 249 pp.

Idso, S. B.: 1981, 'A set of equations for full spectrum and 8- to 14-mm and 10.5- to 12.5-mm, thermal radiation from cloudiness skies', *Water Resources Res.* **17**, 295-304.

Canopy Temperature (CT)

Algorithm

Non-steady State

According to Jones (1992), the leaf temperature within each grid box at non-steady state is written as

$$\frac{d\theta_c}{dt} = \frac{R_{\text{net}} - SH - LH}{\rho_c C_{p,c} l_c} \tag{CT.1}$$

where T_C is the canopy temperature, *t* is the time, *SH* is the sensible heat, *LH* is the latent heat, ρ_C and $C_{p,c}$ are the density and specific heat capacity, respectively, of leaf tissue. l_C is the thickness of a flat leaf (*d*/4 for a cylinder or *d*/6 for a sphere, where *d* is the diameter), and Δz is the spatial interval in the vertical direction.

The sensible heat, *SH*, is given by Norman (1979) and Jones (1992) as

$$SH = \frac{2a\Delta z\rho_a C_{p,a}}{r_b}\left(\theta_c - \theta_a\right), \tag{CT.2}$$

where ρ_a and $C_{p,a}$ are the density and specific heat, respectively, of the air. The factor of two corresponds to the two sides of the leaves.

The latent heat, *LH*, is given as

$$LH = \frac{2a\Delta z\varepsilon\lambda\rho_a}{P\left(r_b + r_s\right)}\left[e_s\left(\theta_c\right) - e\left(\theta_a\right)\right] \tag{CT.3}$$

where ε is the ratio of the molecular weights of water vapor and dry air ($= 0.622$), λ is the latent heat of evaporation ($= 2.45 \times 10^6$ J kg^{-1}), *P* is the surface atmospheric pressure ($= 10^5$ Pa), $e_S(\theta_C)$ is the saturation vapor pressure at the canopy temperature θ_C, and *e* is the in situ vapor pressure.

Given the specific humidity of the air *q* and the surface atmospheric pressure *P*, the vapor pressure in equation (CT.3) is calculated as

$$e = \frac{P}{0.622}q\,. \tag{CT.5}$$

The saturation vapor pressure, $e_s(\theta_a)$, is given as

$$e_s(\theta_a) = 611 \times \exp\left[\frac{17.67(\theta_a - 273.15)}{\theta_a - 29.66}\right]. \qquad \text{(CT.6)}$$

Program

The main subroutine to calculate the canopy temperature (equation3 (CT.1-3)) is named as

CANOPY_TMP(thetac, SH, LH, thetav, RN, u, v, q, tmp_a, flx_Rs, abs_Rs, TMP_RL, TMP_RV, M, Mh)

where **SH** is the sensible heat, **LH** represents the latent heat, thetav represents the air temperature, **RN** is the net irradiance, **u** and **v** are the velocity components of winds, **q** represents the specific humidity, **tmp_a** is the output of the leaf area density, **flx_Rs** is the output of the shortwave radiation flux, **abs_Rs** is the output of the absorption of the shortwave radiation, **TMP_RL** is the longwave radiation, **TMP_RV** is the visible irradiance, **M** is the total number of grid boxes, and **Mh** is the number of grid box within the canopy.

Equation (CT.4) is coded in the subroutine

SV_TMP_SLP(delta,es,thetav)

where **delta** stands for the slope (S) of saturation vapor pressure vs. temperature, **es** is the saturation vapor pressure, and **thetav** is the air temperature at a specified grid box.

The vapor pressure (equation (CT.5)) is coded in the subroutine

VAPOR_PRE(e,q)

where **e** is the output vapor pressure and **q** is the specific humidity.

The saturation vapor pressure (equation (CT.6)) is coded in the subroutine

SAT_VAPOR_PRE(es,thetav)

Reference

Jones, H. G.: 1992, *Plants and Microclimate - A Quantitative Approach to Environmental Plant Physiology*, Cambridge University Press, New York, 428 pp.

Norman, J. M.: 1979, 'Modeling the complete crop canopy', In: *Modification of the Aerial Environment of Crops, ASAE Monograph*, 249-311.

The Governing Equations for the Air (GE)

Algorithm

Under the assumption of horizontal homogeneity, the governing equations of momentum, heat, and moisture of the air, after volumetric and temporal averaging, are given as (Wilson and Shaw, 1977; Raupach and Shaw, 1982; Raupach *et al.*, 1985; Groβ, 1993; Kaimal and Finnigan, 1994)

$$\frac{\partial\langle\overline{u}\rangle}{\partial t} = +f\left(\langle\overline{v}\rangle - \langle\overline{v}_g\rangle\right) - \frac{1}{2}C_D aM\langle\overline{u}\rangle - \frac{\partial\left(\langle\overline{w'u'}\rangle\right)}{\partial z} \tag{GE.1}$$

$$\frac{\partial\langle\overline{v}\rangle}{\partial t} = -f\left(\langle\overline{u}\rangle - \langle\overline{u}_g\rangle\right) - \frac{1}{2}C_D aM\langle\overline{v}\rangle - \frac{\partial\left(\langle\overline{w'v'}\rangle\right)}{\partial z} \tag{GE.2}$$

$$\frac{\partial\langle\overline{\theta}_a\rangle}{\partial t} = \frac{LH+SH}{\rho_a C_{p,a}\Delta z} - \frac{\partial\left(\langle\overline{w'\theta'}\rangle\right)}{\partial z} \tag{GE.3}$$

$$\frac{\partial\langle\overline{q}\rangle}{\partial t} = \frac{LH}{\rho_a \lambda \Delta z} - \frac{\partial\left(\langle\overline{w'q'}\rangle\right)}{\partial z} \tag{GE.4}$$

where u and v are the two horizontal components of winds, θ_a and q are the potential temperature and the specific humidity, respectively, of the air, u_g and v_g are the two geostrophic wind components representing the mean horizontal pressure gradients, M is the mean wind speed ($=\sqrt{\langle\overline{u}\rangle^2 + \langle\overline{v}\rangle^2}$), C_D is the drag coefficient of the canopy, and f_c is the Coriolis parameter ($= 10^4$ s^{-1}). The definitions of the rest of the variables can be referred to the section "***Canopy Temperature***". In the above equations, the brackets and the overbars indicate the volumetric and the temporal means, respectively.

In momentum equations (GE.1,2), the first terms on the right-hand sides represent the deviation of the flows from the mean geostrophic winds. It may be neglected within the roughness sublayer, since both Coriolis effect and mean pressure gradient are several orders smaller than the rest of the terms for the microscale systems. The mean geostrophic winds were defined using the mean horizontal pressure gradients (Stull, 1994):

$$\overline{u}_g = -\frac{1}{f_c\overline{\rho}_a}\frac{\partial\overline{P}}{\partial y} \text{ and } \overline{v}_g = +\frac{1}{f_c\overline{\rho}_a}\frac{\partial\overline{P}}{\partial x}. \tag{GE.5}$$

Notice that LH and SH in equation (GE.3) are just the counterparts in the governing equation for the canopy temperature. This implies that the loss/gain of energy on the foliage due to latent or sensible heat serves as the source/sink to the surrounding air within the canopy.

The last term of equations (GE.1-4) represents the net transport of the quantity by the turbulence. This term is parameterized using Stull's transilient turbulence theory , as discussed in the section "***Parameterization of Turbulent Transport***".

By leaving out the turbulent transport terms for separate consideration, the discretization of equations (GE.1-4) is written in a generic form as

$$\left\langle \bar{\xi}^*(t+\Delta t) \right\rangle = \left\langle \bar{\xi}(t) \right\rangle + F_\xi \Delta t, \qquad \text{(GE.6)}$$

where ξ represents any passive tracer or quantity (u, v, θ, or q), F_ξ represents the external forcings as

$$F_\xi = \begin{cases} +f\left[\langle \bar{v} \rangle - \left\langle \bar{v}_g \right\rangle\right] - \dfrac{1}{2} C_D a M \langle \bar{u} \rangle & \text{for } \xi = u \\ -f\left[\langle \bar{u} \rangle - \left\langle \bar{u}_g \right\rangle\right] - \dfrac{1}{2} C_D a M \langle \bar{v} \rangle & \text{for } \xi = v \\ \dfrac{LH+SH}{\rho_a C_{p,a} \Delta z} & \text{for } \xi = \theta \\ \dfrac{LH}{\rho_a \lambda \Delta z} & \text{for } \xi = q \end{cases} . \qquad \text{(GE.7)}$$

The asterisk in equation (GE.6) represents the intermediate step in the numerical integration.

Program

The subroutines for the intermediate integration of momentum, heat, and moisture equation (GE.6), respectively, are named as

FORCE_VEL(u,v,ug,vg,M)

FORCE_TMP(u, v, thetav, thetac, q, SH, LH, RN, tmp_a, flx_Rs,

abs_Rs, TMP_RL, TMP_RV, M, Mh)

FORCE_HMD(q,LH,M,Mh)

where **u** and **v** represent the two components of winds, **ug** and **vg** represent the two components of geostrophic winds, **M** represents the total number of grid boxes, **thetav** and **thetac** represent the

temperatures of air and leaves, respectively, **q** represents the specific heat of air, **LH** and **SH** represent the latent and sensible heat, respectively, **RN** and **RV** represent the net and visible irradiance within each grid box, and **Mh** represents the number of grid boxes within the canopy.

Reference

Groβ, G.: 1993, *Numerical Simulation of Canopy Flows*, Springer-Verlag, New York, 167 pp.

Kaimal, J. C. and Finnigan, J. L.: 1994, *Atmospheric Boundary Layer Flows - Their Structure and Measurement*, Oxford University Press, New York, 289 pp.

Raupach, M. R., Coppin, P. A., and Legg, B. J.: 1986, 'Experiments on scalar dispersion within a model plant canopy. Part I. The turbulence structure', *Bound.-Layer Meteor*. **35**, 21-52.

Raupach, M. R., and Shaw, R. H.: 1982, 'Averaging procedures for flow within vegetation canopies', *Bound.-Layer Meteor*. **22**, 79-90.

Wilson, N. R., and Shaw, R. H.: 1977, 'A higher order closure model for canopy flow', *J. Appl. Meteorol.* **42**, 1197-1205.

Parameterization of Turbulent Transport (TT)

Algorithm

The *translient turbulence theory* (TTT) (Stull, 1984, 1985, 1986, 1990, 1993; Stull and Hasegawa, 1984; Stull and Driedonks, 1987) was applied to the parameterization of the turbulent transport terms in equations (GE.1-4).

Using index i and j represent the index of grid box, TTT suggests that the turbulence mechanisms respond to the instability voluntarily by mixing the corresponding quantities between grid box j and any other grid box i during the same time interval Δt. If c_{ij} represents the fraction of air in box i that came from j during time interval Δt, then the new concentration at box i after the mixing can be calculated by the summation of the mixing from over all n grid boxes in the column, which is

$$\bar{\xi}_i(t+\Delta t) = \sum_{j=1}^{n} c_{ij}(t,\Delta t)\bar{\xi}_j^*(t+\Delta t) \tag{TT.1}$$

which tells us that when air is mixed into box i from box j, the air carries with it an amount of $c_{ij}(t,\Delta t)$ of the tracer with concentration $\bar{\xi}_j$, which can be recognized as an $n \times n$ matrix of mixing coefficient and is called a *transilient matrix*.. The diagonal elements of the matrix, $c_{ii}(t,\Delta t)$, represents the fraction of air that remains in box i. Since $\bar{\xi}_j^*$ may be seen as an $n \times 1$ matrix, equation (TT.1) prescribes simple matrix multiplication.

As suggested by Stull and Driedonks (1987) followed by other researchers (Chrobok *et al.*, 1992; Cuxart and Soler, 1994), the following parameterization for the exchange of matrix c_{ij} was incorporated into the model

$$c_{ij} = \begin{cases} m_j Y_{ij} / \|Y\| & \text{for } i \neq j \\ 1 - \sum\limits_{\substack{j=1 \\ j\neq i}}^{n} c_{ij} & \text{for } i = j \end{cases} \tag{TT.2}$$

with the constraints:

$$\sum_{j=1}^{n} c_{ij} = 1, \qquad \sum_{i=1}^{n} \frac{m_i}{m_j} c_{ij} = 1 \tag{TT.3}$$

for the conservation of air mass and state, where Y_{ij} is called the mixing potential, and m_i and m_j represent the air mass in ith and jth grid boxes, respectively. With the presence of the canopy, the mixing potential may be modified (Stull, 1993) as

$$Y_{ij} = Y'_{ij} \prod_{k=i}^{j-1} \left(1 - \gamma_k\right) \tag{TT.4}$$

for $j > i$, If $j < i$, then the product will be from $k = j$ to $k = i - 1$, where γ_k is defined as the interference coefficient that varies between 1.0 for total interference by plants, to 0.0 for no interference of vertical eddy motions, and Y'_{ij} has the same definition as Y_{ij} (see equation (TT.8) below). The interference coefficient may be associated with the cumulative leaf area index as

$$\gamma_k = \frac{\left|L_{k+1/2} - L_{k-1/2}\right|}{\mathrm{LAI}} \tag{TT.5}$$

The evaluation of Y_{ij} was done following Stull and Driedonks (1987) using nonlocal form of TKE equation, except that the TKE equation was defined in the roughness sublayer. According to Raupach *et al.* (1986), the TKE equation is given as

$$\frac{\partial E}{\partial t} = -\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z} + \frac{g}{\overline{\theta}}\overline{w'\theta'} - \frac{\partial\left(\overline{w'E}\right)}{\partial z} - \frac{1}{2}C_D a\left(\overline{u}^3 + \overline{v}^3\right) - \varepsilon \tag{TT.6}$$

The nonlocal analogous expression may be written as

$$\frac{\Delta_t E_{ij}}{E_{ij}} = \left[\frac{\overline{\left(-u'w'\right)}_{ij}}{E_{ij}}\left(\frac{\Delta \overline{u}}{\Delta z}\right)_{ij} + \frac{\overline{\left(-v'w'\right)}_{ij}}{E_{ij}}\left(\frac{\Delta \overline{v}}{\Delta z}\right)_{ij} + \frac{g}{\overline{\theta}_{ij}}\frac{\overline{\left(w'\theta'\right)}_{ij}}{E_{ij}} + \frac{1}{\Delta z_{ij}}\left(\frac{\Delta\left(-\overline{w'E}\right)}{E}\right)_{ij} + \frac{\left(-\frac{1}{2}\right)C_D \overline{a}_{ij}\left(\overline{u}_{ij}^3 + \overline{v}_{ij}^3\right)}{E_{ij}} - \frac{\varepsilon_{ij}}{E_{ij}}\right]\Delta_t t \tag{TT.7}$$

where $\overline{\theta}_{ij}$, $\overline{a}_{ij}$, $\overline{u}_{ij}$, and $\overline{v}_{ij}$ are the mean potential temperature, leaf area density, latitudinal and longitudinal velocity components between layers i and j, respectively.

The mixing potential is then prescribed as

$$Y_{ij} = \begin{cases} \dfrac{T_0 \Delta_t t}{(\Delta z)^2_{ij}} \left\{ (\Delta u)^2_{ij} + (\Delta v)^2_{ij} - \dfrac{g(\Delta z)_{ij}}{R_c \bar{\theta}_{ij}} (\Delta\theta)_{ij} + \left[(\Delta u)_{ij} \left|(\Delta u)_{ij}\right| + (\Delta v)_{ij} \left|(\Delta v)_{ij}\right| \right] + \dfrac{1}{2} C_D \bar{a}_{ij} \overline{M}^3_{ij} T_0 \right\} \\ \qquad - \dfrac{D \Delta_t t}{T_0} & \text{for } i \neq j \\ \max\left(Y_{i,i-1}, Y_{i,i+1}\right) + Y_{\text{ref}} & \text{for } i = j \end{cases}$$

(TT.8)

and $\|\cdot\|$ denotes the maximum norm such as

$$\|Y\| = \max_i^n \left(\sum_{j=1}^n Y_{ij} \right). \qquad \text{(TT.9)}$$

In the above formulations, T_0 represents a time scale of turbulence, R_C is analogous to a critical Richardson number above which turbulent mixing is zero ($Y_{ij} = 0$), D is a dimensionless factor that scales the dissipation, Y_{ref} is a reference mixing potential that accounts for the internal mixing within a grid box, and $M_{ij} = \sqrt{\bar{u}^2_{ij} + \bar{v}^2_{ij}}$ is the mean wind speed between ith and jth box..

Under the circumstance when $i = j$, Y_{ii} may be interpreted as the subgrid (internal) mixing potential for eddies smaller than the size of one grid box. As explained by Stull (1984) and Stull and Driedonks (1987), Y_{ii} ought to be made larger than any other element in the (Y) matrix and the values of Y_{ij} elements increase monotonically from the value of the upper right-most element in the (Y) matrix toward the values on the main diagonal, i.e., $Y_{ii} > Y_{i,i+1}$ in order to avoid the situation of convective overturn. As the first trial, values of $R_0 = 0.21$, $D = 1$, $Y_{\text{ref}} = 1000$, $T_0 = 1000$ from the literature were used, although the parameters in the transilient matrix have to be determined accordingly by the sensitivity study.

In equation (TT.4), two terms associated with the presence of the canopy are turbulent transport, $\dfrac{\partial\left(\overline{w'E}\right)}{\partial z}$, and the wake production, $\dfrac{1}{2} C_D a\left(\bar{u}^3 + \bar{v}^3\right)$. The turbulent transport term acts as a significant sink for turbulent kinetic energy at the top of the canopy and up to about $z = 2H$, and source in the canopy (Kaimal and Finnigan, 1994; Leclerc *et al.*, 1990; Meyers and Baldocchi, 1991), where both shear

and shear production have fallen to insignificantly low values. This term represents the non-local influences of TKE and is important in maintaining turbulent kinetic energy levels in the canopy. It also associates with the large values of skewness observed in the lower canopy. The wake production term is the representation of the drag by the canopy which converts mean kinetic energy to turbulent energy. It accounts for the local variations in shear stress doing work against local variations in mean strain rates. As has been discussed by Kaimal and Finnigan (1994), this term reaches its maximum in the upper canopy and disappears above the canopy and toward the ground surface.

The fluxes of variable ξ is given following Stull (1994) as

$$\overline{w'\xi'}(k) = \overline{w'\xi'}(k-1) + \left(\frac{\Delta z}{\Delta t}\right)\sum_{j=1}^{n} c_{kj}\left(\bar{\xi}_k - \bar{\xi}_j\right) \qquad \text{(TT.10)}$$

Program

The subroutine to calculate the mixing potential (equations (TT.6,7)) are named as

MIXING_POT(Y,u,v,thetav,M)

where **Y** represents the mixing potential as the output, the rest of the variables are the same as in the section of "***The Governing Equations for the Air***".

The subroutine for the transilient matrix is named as

TranMTRX(c,Y,M)

where **c** is the transilient matrix as the output, **Y** and **M** are the inputs.

The mixing processes (equation (TT.1)) were achieved using subroutine

TT_MIXING(ξ,temp,c,M)

where ξ represents any variable (u, v, q, or q), and **temp** is a temporary variable which has the same dimension as ξ.

The fluxes (equation (TT.8)) were calculated using subroutine

FLUXES(ξ,wξ,c,M)

where **w**ξ represents the output vertical fluxes of the variable ξ.

Reference

Chrobok, G., Raasch, S., and Etling, D.: 1992, 'A comparison of local and non-local turbulence closure methods for the case of a cold air outbreak', *Bound.-Layer Meteorol.* **58**, 69-90.

Cuxart, J., and Soler, M. R.: 1994, 'A comparison between transilient turbulence theory and the exchange coefficient model approaches', *Bound.-Layer Meteorol.* **67**, 251-276.

Kaimal, J. C. and Finnigan, J. L.: 1994, *Atmospheric Boundary Layer Flows - Their Structure and Measurement*, Oxford University Press, New York, 289 pp.

Leclerc, M. Y., Beissner, K. C., Shaw, R. H., Hartog, G. Den., and Neumann, H. H.: 1990, 'The influence of atmospheric stability on the budgets of the Reynolds stress and turbulent kinetic energy within and above a deciduous forest', *J. Appl. Meteorol.* **29**, 916-933.

Meyers, T. P., and Baldocchi, D. D.: 1991, 'The budgets of turbulent kinetic energy and Reynolds stress within and above a deciduous forest', *Agric. For. Meteorol.* **50**, 1-16.

Raupach, M. R., Coppin, P. A., and Legg, B. J.: 1986, 'Experiments on scalar dispersion within a model plant canopy. Part I. The turbulence structure', *Bound.-Layer Meteor.* **35**, 21-52.

Stull, R. B.: 1984, 'Transilient turbulence theory: Part I: The concept of eddy-mixing across finite distances', *J. Atmos. Sci.* **41**, 3351-3367.

Stull, R. B.: 1985, 'Reply', *J. Atmos. Sci.* **42**, 2070-2072.

Stull, R. B.: 1986, 'Transilient turbulence theory: Part III: Bulk dispersion rate and numerical stability', *J. Atmos. Sci.* **43**, 50-57.

Stull, R. B.: 1990, 'Nonlocal Turbulent Mixing: Measurement and Parameterization of Transilient Matrices', *The Ninth Symposium on Turbulence and Diffusion*, April 30 - May 3, Roskilde, Denmark, Published by the American Meteorological Society, Boston, Mass.

Stull, R. B.: 1993, 'Review of transilient turbulence theory and nonlocal mixing', *Bound.-Layer Meteorol.* **62**, 21-96.

Stull, R. B.: 1994, *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers, Boston, 666 pp.

Stull, R. B., and Driedonks, A. G. M.: 1987, 'Application of the transilient turbulence parameterization to atmospheric boundary-layer simulations', *Bound.-Layer Meteorol.* **40**, 209-239.

Stull, R. B., and Hasegawa, T.: 1984, 'Transilient turbulence theory.Part II: Turbulent adjustment', *J. Atmos. Sci.* **41**, 3368-3379.